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OPTICALLY DETECTED CYCLOTRON RESONANCE STUDIES OF ERBIUM AND YTTERBIUM DOPED InP

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ABSTRACT

Optically Detected Cyclotron Resonance (ODCR) studies of recombination processes in erbium and ytterbium doped InP are presented. The experimental results obtained allow to verify the excitonic mechanism of 4f-shell excitation. The Yb^{3+} intra-shell emission is induced by a nonradiative recombination of the Yb bound exciton due to the impurity Auger effect. The energy transfer mechanism from shallow donor - acceptor pairs to Yb is proved to be inefficient. The main effect of hot carriers on Yb emission is related to impact ionization of impurity bound excitons and shallow donors, which enhances the free carrier recombination via Yb. The ODCR results for Er doped InP indicate that exciton - related excitation mechanism is less efficient, if present. It is shown that Auger - type nonradiative recombination limits the efficiency of the Yb and Er intra - shell emissions.

INTRODUCTION

Rare earth (RE) ions are characterized by an unfilled 4f - shell, which is an inner shell and, therefore, screened by external $5s^2$ and $5p^6$ shells. Because of this screening, the crystal field introduces only small corrections to the multiplet structure of RE ions. Also the coupling to lattice vibrations is weak. In consequence, very sharp, matrix - and temperature - independent optical transitions are observed. These properties of RE ions, once they are introduced into III - V semiconductors, can be utilized for obtaining efficient light emitting devices with RE emission induced by injection of minority carriers.

Among different RE ions erbium and ytterbium belong to the most studied. For example, $1.54\mu m$ $^4I_{13/2} \rightarrow ^4I_{15/2}$ intra - shell emission of Er can be used for carrier - pumped optoelectronic devices for silica - based fiber communication.[1-4]

One of the most important tasks on the way to efficient RE doped devices is to optimize the RE excitation mechanism. Several such mechanisms were shown to be efficient for RE ions in different hosts. These include, first of all, the direct RE excitation (4f - 4f transition), as well as a range of indirect processes. The latter are due to energy transfer from other center(s), e.g. other RE ion,[5] or a recombining donor - acceptor pair (DAP).[6,7] For carrier injection devices two other mechanisms may be relevant, i.e. the impact excitation[8] and impact ionization[9] processes. The latter was found to be important for wide bandgap II - VI electroluminescence displays. The theoretical background for RE excitation mechanisms was given recently by Schmitt - Rink ét al.[10]

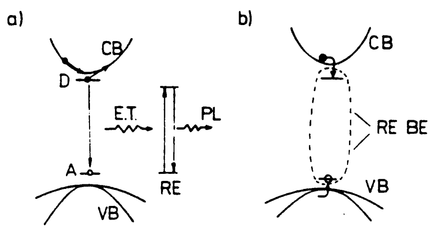
In this paper we verify the high efficiency of recently proposed new RE excitation mechanism in which efficient RE emission can be induced via energy transfer from RE bound exciton[11] (RE BE) to 4f core states of RE ion. The mechanism of such transfer was explained previously by Robbins and Dean.[12] The RE ion in its 3+ charge state is an isovalent (isoelectronic) dopant when substituting the cation in III - V compound. Such centers may introduce a short range attractive potential for one type of free carriers and, thus, bind an exciton. Once the first carrier is localized by the short range potential, the second is trapped by a long range Coulomb attractive potential of the first carrier, forming RE BE. This exciton decays nonradiatively transferring its energy to RE core states. Such process is called an impurity (defect) Auger recombination.[11,12]

The property of exciton binding was predicted recently for Yb[13] and Er[14] in InP. We verify here the efficiency of the exciton - related RE excitation mechanism by performing ODCR measurements. The ODCR method, introduced previously for low field cyclotron resonance (CR) experiments,[15,16] can be used for impact ionization studies of excitons and shallow impurities.[17] In such a case, the microwave field is used to accelerate the photo - generated free carriers, which can reach an energy sufficient for impact of excitons and shallow impurity centers. The heating up of free carriers is the most efficient at the CR condition.

RESULTS AND DISCUSSION

Figure 1 explains the concept of the ODCR experiment applied to verify the relative importance of different excitation processes. Impact of shallow donors of InP should deactivate the RE (Yb,Er) emission if the DAP - to - RE energy transfer is important, as concluded previously.[7] However, if these RE ions can bind an exciton, RE emission will be stimulated under the impact of shallow donors. This will be due to enhanced RE exciton formation once the competing carrier trapping processes are deactivated.

The photoluminescence (PL) spectra of Er and Yb doped InP layers are shown in Fig. 2. These measurements were performed on MOCVD grown InP layers under the above - bandgap excitation. All details on the growth procedure and the experimental set up can be found elsewhere.[13,18] The PL spectrum of InP:Yb consists of donor BE (DBE), at 1417.5 meV, and DAP, at 1387.5 meV and 1344.6 meV (TO phonon replica), emissions. In the case of Er doped material, the DBE PL is much weaker.



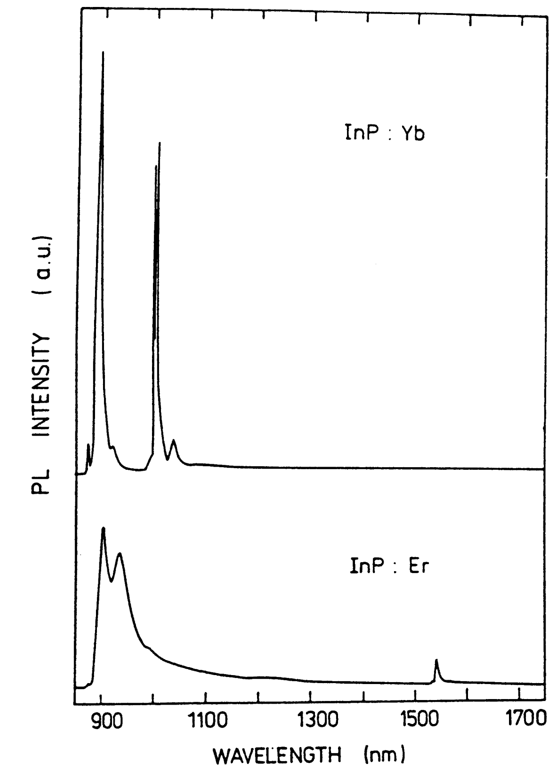
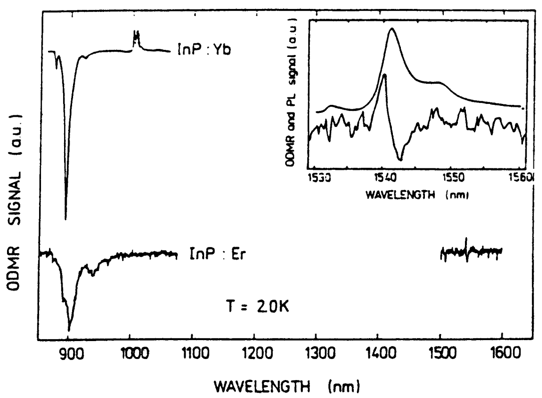


Figure 1 (left)
The concept of the ODCR experiment. Impact of shallow donors reduces the efficiency of DAP - RE energy transfer (a), whereas it enhances, due to increased free electron concentration, the RE bound exciton formation (b).

Figure 2 (right)
Photoluminescence spectra of Yb and Er doped InP measured at 1.2 K under the 514.5 nm Ar^+ laser excitation (50 mW).

Figure 3 presents the influence of microwaves on the PL spectra. These data were obtained by setting magnetic field at the broad CR band and measuring PL changes in phase with the chopped microwave power. A relatively high chopping frequency was used (713 Hz) to minimize sample heating.[17] Fig. 3 shows that the DBE and DAP emissions are quenched and that the Yb^{3+} PL is enhanced once microwave power is turned on.



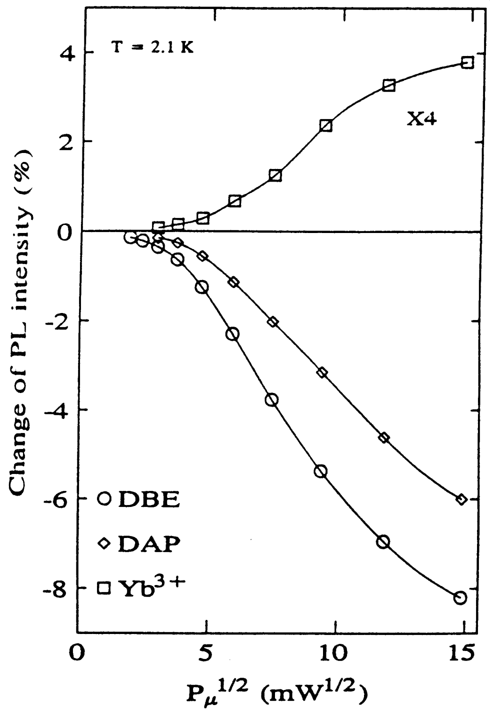


Figure 3 (left)
The spectral dependence of the microwave induced impact ionization processes in InP:Yb and InP:Er. In the inset the Er^{3+} PL and the PL change are shown in more detail.

Figure 4 (right)
Microwave power dependence of the PL intensities for three different recombination processes (DBE, DAP and Yb^{3+}). The experiment was performed at 2.1 K, constant excitation intensity (514.5 nm, 50 mW), magnetic field set at the broad CR signal, and lock-in detection in phase with chopped microwave power (35 GHz) at 730 Hz.

This effect shows a threshold dependence on the microwave power applied (Fig. 4), which indicates that the impact ionization mechanism is responsible for the observed changes of the PL intensities.[17]

The data depicted in Fig. 3 and 4 clearly show that the DAP - to - RE transfer is not important in our crystals and confirm the high efficiency of the exciton - related RE excitation mechanism.[18] It is observed that the impact ionization of DBEs and shallow donors, which results in an increase of the free carrier concentration, enhances the Yb^{3+} PL. The RE exciton formation is enhanced with the reduction of the probability of electron trapping by shallow donor states. For higher microwave powers this effect saturates, which is in agreement with the previous estimations of small exciton and carriers binding energies.[13] For such powers the second, loosely bound carrier (hole) can be ionized by impact, i.e. the exciton dissociates.

It was suggested previously that the decay time of an excited RE ion can be ruled by the Auger - type energy transfer to either bound or free carriers.[19,20] This is confirmed by our results shown in Fig. 3. We observe that impact of DBEs and DAPs does not enhance the Yb^{3+} emission equally. A 5 - 6 % decrease in the overall PL intensity is observed once the maximal microwave power is turned on. This means that the impact - induced increase of the free carrier concentration stimulates not only the RE BE formation, but some nonradiative recombination, as well. We take this observation as evidence for the high efficiency of Auger - type recombination processes. It was shown previously that the Auger - type transfer to free electrons is about two orders in magnitude more efficient than that to shallow - donor bound electrons.[21] By impact ionization of shallow donors we, therefore, not only stimulate the RE BE formation, but simultaneously replace one nonradiative recombination channel by another, more efficient (energy transfer from excited RE ions to free electrons).

The data shown in Fig. 3 indicate higher efficiency of this process for Er^{3+}. Here an asymmetric, derivative - like response to microwave power is observed. The intensity of Er^{3+} PL rises at the higher energy part of the emission and gives a negative signal at lower part. Separate PL measurements prove that the latter reflects the small (1%) decrease of the PL intensity observed once microwaves are turned on. The rise at the higher energy part of the spectrum indicates that the Er^{3+} PL broadens slightly once microwaves are applied. This is probably due to some lattice heating by the accelerated free carriers. The effect is minimized when using a relatively high chopping frequency. The observed quenching of the DBE and DAP emissions (Fig. 3 and 4) is, thus, dominated by the impact processes as confirmed by the threshold dependence on the microwave power. We conclude, therefore, that the observed quenching of the Er PL is not due to the weak lattice heating. Our data indicate that the postulated exciton - related excitation mechanism is less efficient for Er^{3+} than that for Yb^{3+}. Due to this fact, the Auger - type energy transfer processes deactivate the Er PL resulting in the observed decrease of its intensity once the microwave power is turned on. We assumed here that, similarly to the case of Yb, DAP - to - Er energy transfer is not important.

Concluding, by performing the ODCR experiments, we verified the high efficiency of the excitonic excitation mechanism of Yb^{3+} PL. Our data indicate also that the Auger - type energy transfer processes limit the efficiency of RE emissions. This is an important draw - back for the application of the RE doped III - V material for carrier - injection devices.

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